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PROPERTIES OF MATERIALS
FOR SUBMILLIMETER MASERS

by

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REPORT 1093-12

REPORT
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THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
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Cooperator	National Aeronautics and Space Administration 1520 H Street, Northwest Washington 25, D.C.
Grant No.	NsG-74-60
Investigation of	Receiver Techniques and Detectors for Use at Millimeter and Submillimeter Wavelengths
Subject of Report	Properties of Materials for Submillimeter Masers*
Submitted by	W.S.C. Chang and R.F. Rowntree Antenna Laboratory Department of Electrical Engineering
Date	5 February 1963

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With the invention of lasers, there has been an increasing interest in the possibility of developing a submillimeter maser. This paper discusses first the particular conditions that are necessary to successfully operate a solid-state submillimeter maser, and second the measured properties of the host lattice and the cavities that could be used for such a development.

Consider first the usual condition for oscillation of any laser in an isotropic medium.[1,2]

$$0.00395\,\frac{Q\,F_{st}\lambda}{\epsilon\Delta f_{st}}\left(\frac{g_t}{g_s}N_s - N_t\right) > 1, \qquad (1)$$

in which, in Gaussian units,

Q = cavity Q

F_{st} = oscillator strength between the signal and the terminal energy levels

λ = wavelength

Δf_{st} = line width of the transition

g_t, g_s = statistical weights of the terminal and the signal energy levels

N_s, N_t = population per unit volume of the signal and terminal states

ϵ = dielectric constant of the medium.

The transition between the signal and the terminal levels is assumed to have a Gaussian line shape. The quantity, $F_{st}/\Delta f_{st}$, is related to the experimentally measurable resonant absorption coefficient, K_{st}, by

$$(2) \qquad \frac{F_{st}}{\Delta f_{st}} = \frac{K_{st}\sqrt{\epsilon}}{0.0248\left(N_t^o - \frac{g_t}{g_s} N_s^o\right)} ,$$

where N_t^o is the population density of the terminal level at thermal equilibrium. Therefore, one can define a resonance absorption Q, Q_{abs}, at $\lambda = (E_s - E_t)/h$ as

$$(3) \qquad Q_{abs} = \frac{2\pi\sqrt{\epsilon}}{K_{st}\lambda} , ^{+}$$

to simplify the condition for oscillation to

$$(4) \qquad \frac{Q}{Q_{abs}} \cdot \frac{\left[\frac{g_t}{g_s} N_s - N_t\right]}{\left[N_t^o - \frac{g_t}{g_s} N_s^o\right]} > 1 .$$

Equation (4) shows clearly the difficulties that one must overcome in developing a submillimeter maser, namely (a) to obtain a high cavity Q, (b) to obtain a low Q_{abs}, and (c) to obtain a reasonable population inversion ratio. However, one finds very little information of the kind mentioned above in this frequency range. At The Ohio State University, we have made detailed measurements of various host lattices in order to predict the achievable Q of a Fabry-Perot cavity in this far-infra-red/submillimeter region. We are now in the process of measuring the K_{st} and the Q_{abs} of the Stark-split levels of various active materials. But we have not yet attempted to achieve the population inversion.

+ Q_{abs} has the physical meaning as the ratio of the "2πf x stored energy" to the "energy dissipated per second through the resonance absorption processes" in the laser material.

Let us consider the achievable Q of the Fabry-Perot cavity in this frequency range. Clearly,[3,4]

$$\frac{1}{Q} = \frac{1}{Q_{ref}} + \frac{1}{Q_{\epsilon}} + \frac{1}{Q_d}$$

where

Q_{ϵ} = cavity Q due to the dielectric loss = $\frac{2\pi\sqrt{\epsilon}}{\alpha\lambda}$

Q_{ref} = cavity Q due to the reflectivity of the end surface = $\frac{2\pi d\sqrt{\epsilon}}{\lambda(1-R)}$,

and Q_d = cavity Q due to the diffraction loss = $\frac{2\pi d\sqrt{\epsilon}}{\lambda\,\delta_d}$,

in which α is the absorption coefficient of the host lattice; d is the separation of the Fabry-Perot surfaces; R is the power reflection coefficient of the end surface; and δ_d is the percentage power loss per transit as calculated by Fox and Li, and Boyd and Gordon.

In the visible region, Q_{ϵ} is usually so large that it can be neglected. However, many crystals have such strong lattice absorption bands in the far-infra-red that one of the most important steps in developing a submillimeter maser is to measure the dielectric properties of laser materials in order to determine Q_{ϵ}. Figures 1 to 6 show the refractive indices, the absorption coefficients, and the percent transmission of $CaWO_4$, Al_2O_3, MgO, and CaF_2 measured on the Ohio State University submillimeter spectrometer,[5,6] and by others.[7,8] These data represent the measured results from many samples and many data points, at 300°K and 90°K. The refractive indices were calculated from the measured "channeled spectra" of the power transmitted through the various samples. The absorption coefficients were calculated from the point by point transmission data after deducting the reflection losses. Low temperature dewars were used to cool the samples. Grids of gold (width 0.010 mm, spacing 0.025 mm) deposited on sheet Mylar were used as polarizers. The detailed descriptions of the experiments are given elsewhere.[5,6] From these data, we can deduce immediately that the Q_ϵ would be limited to 2×10^2 and 2×10^3 in $CaWO_4$ and MgO, respectively, at 300^oK and to approximately 2×10^3 and 6×10^4 at 90^oK, at frequencies of $20\ cm^{-1}$ or higher. Al_2O_3 has similar properties. Lower values of Q_ϵ are expected from CaF_2. From the improvement of absorption coefficient obtained from 300^oK to 90^oK, it appears that considerably higher values of Q_ϵ are achievable if the entire cavity is cooled down to the liquid helium temperature.

On the other hand, the Q_{ref} can be made to exceed 10^5 at submillimeter wavelengths, for $d \geq 5$ cm, because of the high reflectivity, R, available by using metal grids or solid metal with holes as the end reflector of the Fabray-Perot cavity.[9,10] The Q_d may become a limiting factor on cavity Q, depending upon the ratio $\frac{a^2\sqrt{\epsilon}}{d\lambda}$ where a is the radius of the Fabry-Perot end surface.[3,4] According to the calculation made by Fox and Li, we can see that the cavity Q of the TEM_{oo} mode a submillimeter Fabry-Perot planar cavity would be limited to 10^4 with $d \cong 5$ cm at frequencies lower than $17\ cm^{-1}$ where $\frac{a^2\sqrt{\epsilon}}{d\lambda}$ is smaller than 3. On the other hand, the confocal cavity would yield a considerably higher Q_d.

Figure 7 shows a comparison of these Q factors in a typical laser cavity ($TEM_{o,o}$ mode) using MgO or $CaWO_4$ as the sample material. From this figure we can conclude that the Q factor of a submillimeter plane-Fabry-Perot cavity at the liquid helium temperature would probably be limited to 10^4 by the host lattice absorption.

It follows that the successful development of a submillimeter maser must depend upon the selection of an active material that would have a $Q_{abs} = 10^3$ (i.e., $K_{st} \cong 1\ cm^{-1}$) or better, with a population inversion ratio of 10% or better. It also means that any material in which an electric dipole transition does not occur will probably not make a good submillimeter maser material. From the existing submillimeter spectroscopic data in solids reported by Tinkham and others, K_{st} of this order of magnitude should be available in many materials. The major obstacle would appear to be the achievement of a reasonable population inversion ratio.

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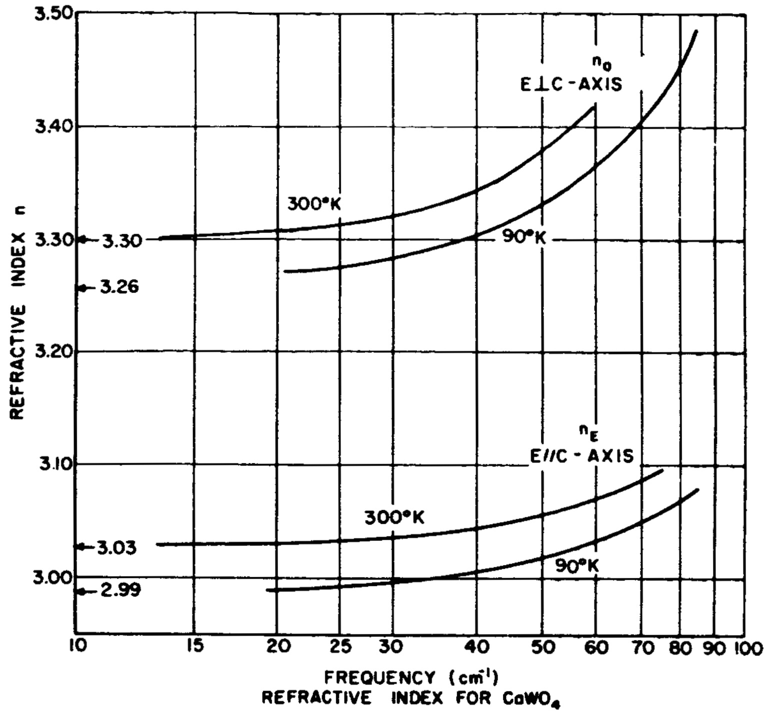

Fig. 1. Refractive index for $CaWO_4$.

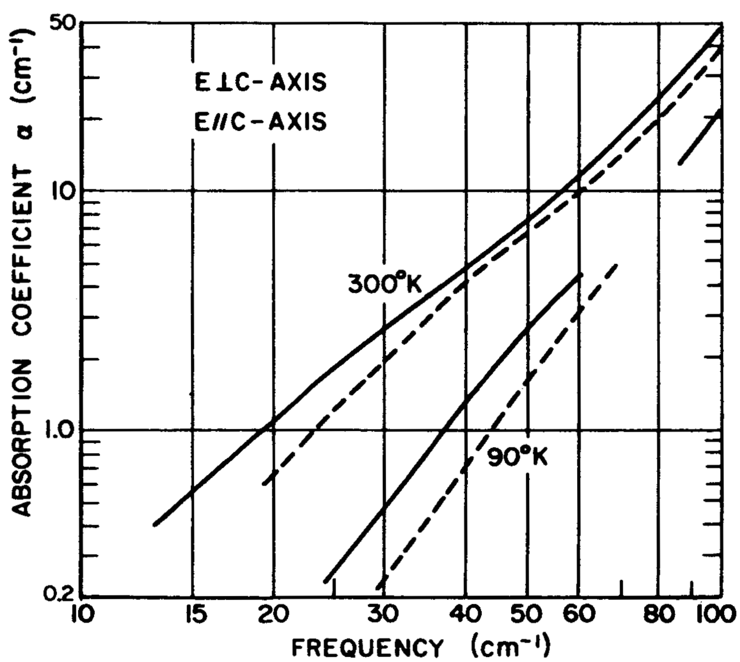

Fig. 2. Absorption coefficient of $CaWO_4$.

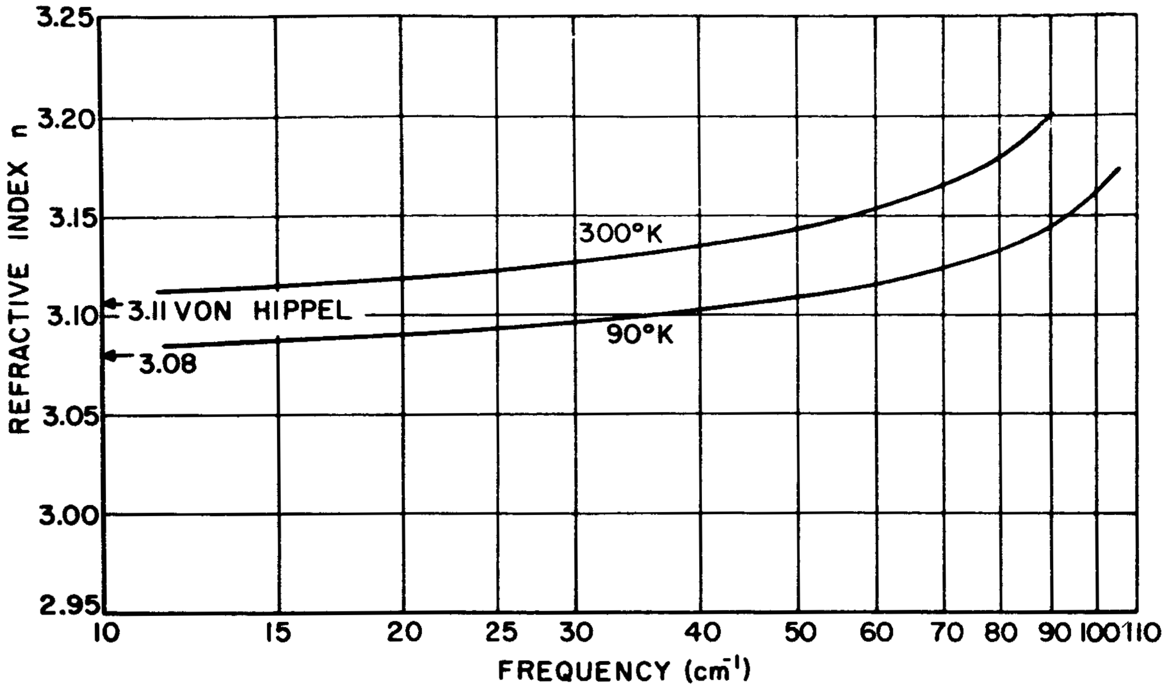

Fig. 3. Refractive index of MgO.

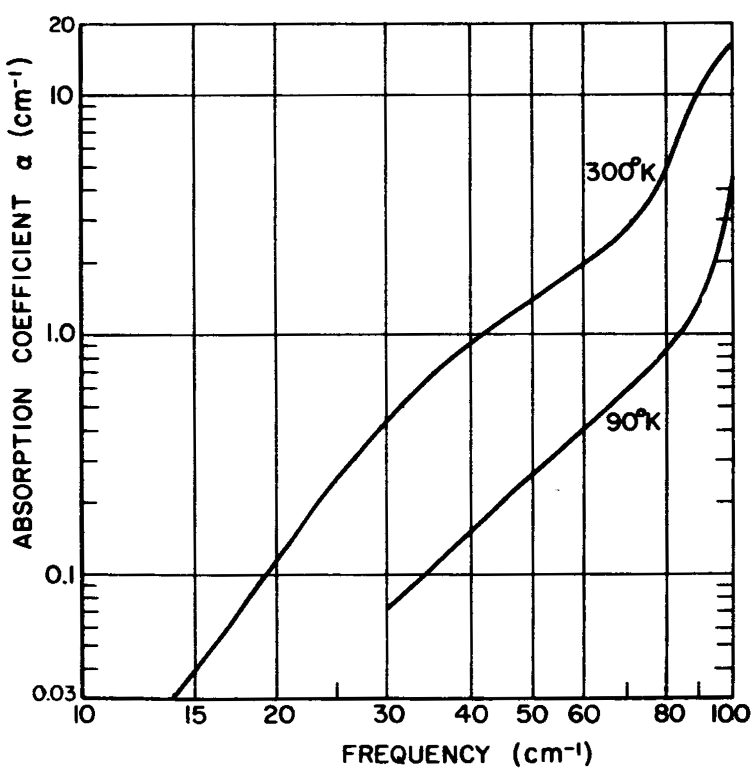

Fig. 4. Absorption coefficient of MgO.

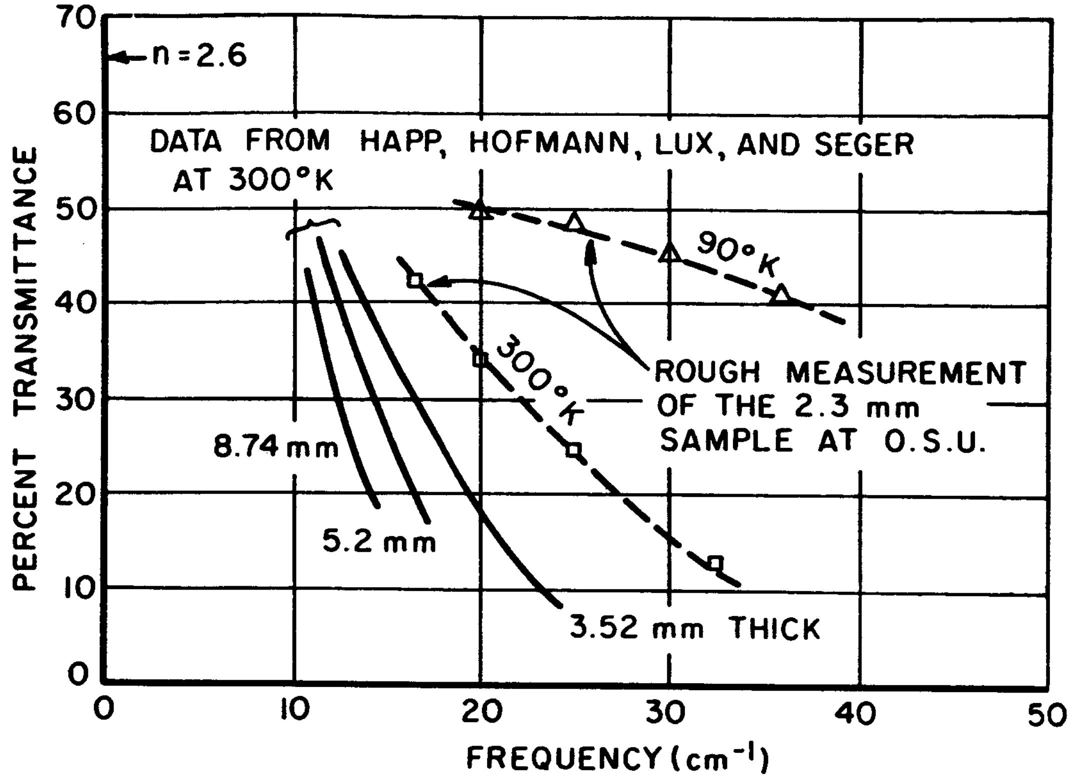

Fig. 5. Transmission of CaF_2.

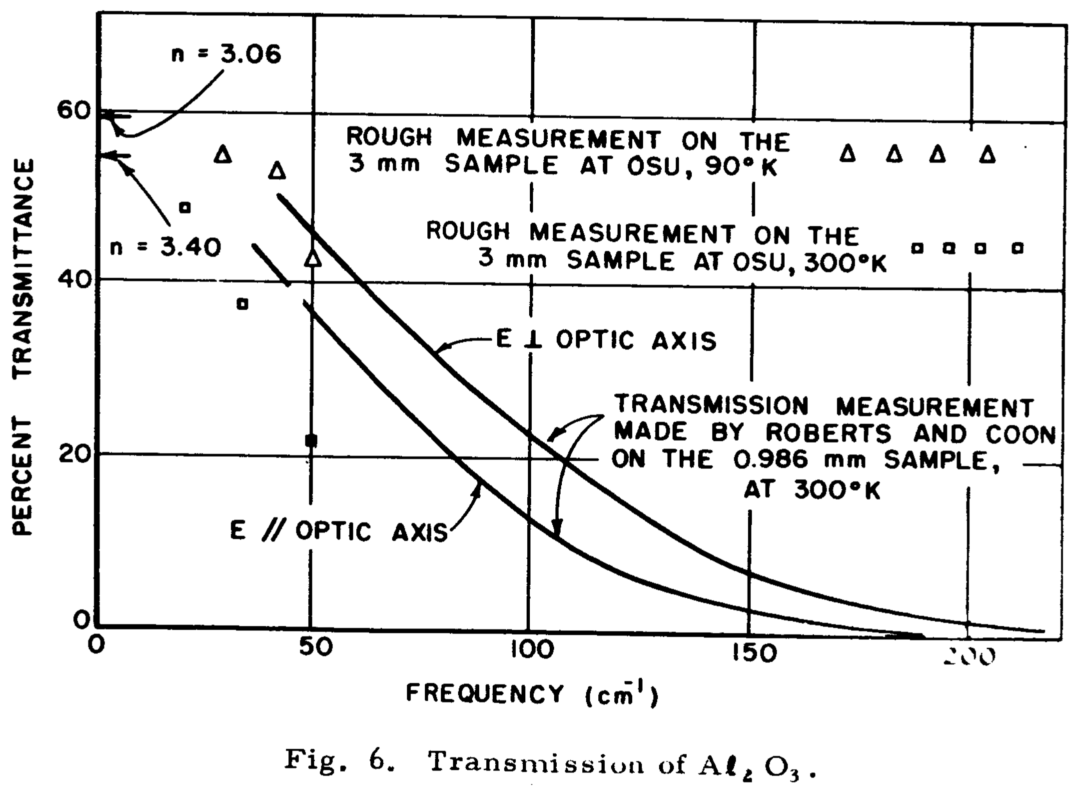

Fig. 6. Transmission of Al_2O_3.

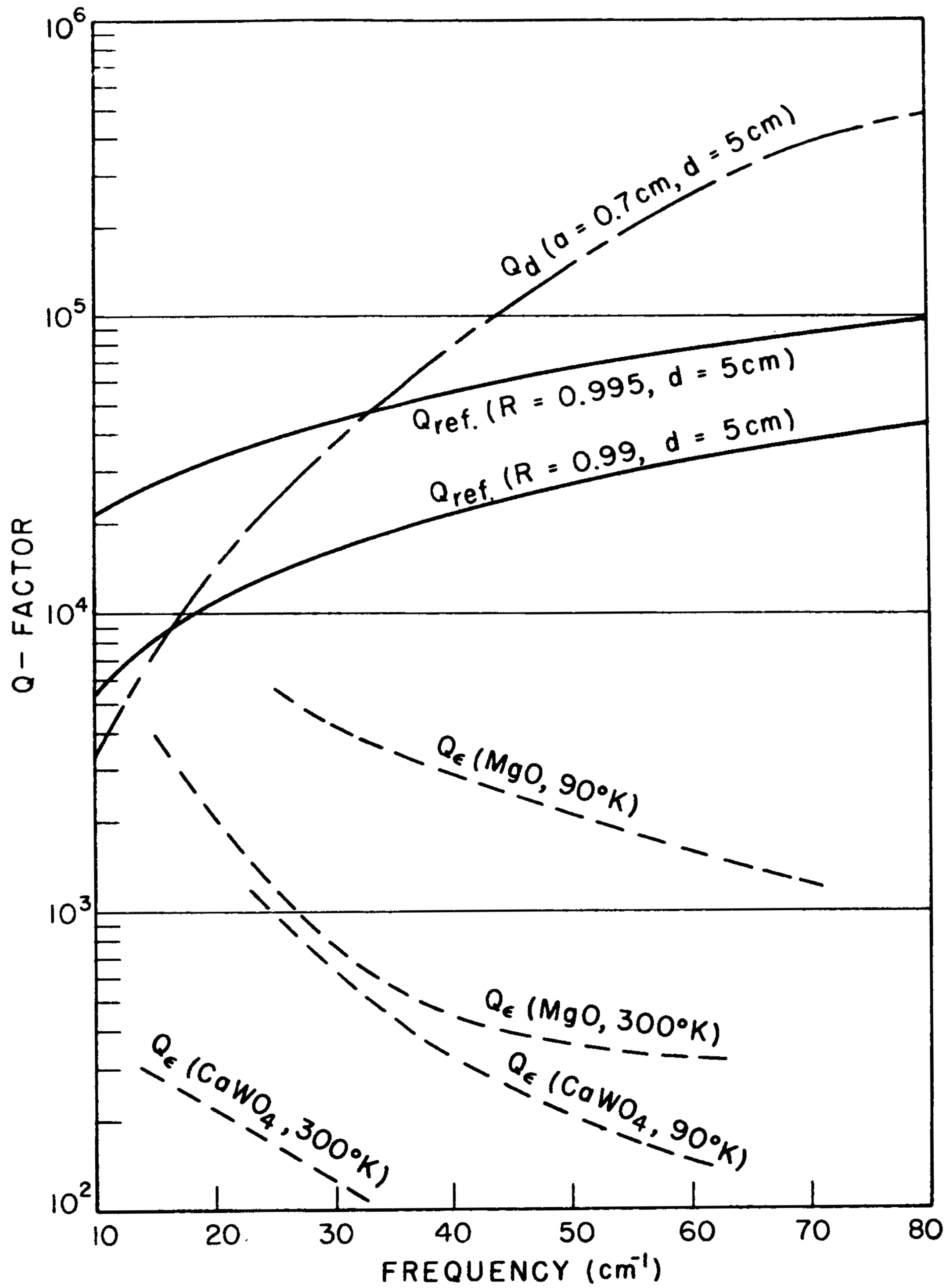

Fig. 7. A comparison of Q factors in a typical laser cavity.